Performance Characterization of a Shape Memory Composite Mirror

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Abstract- **Deployable optics comprised of an electroformed, replicated nickel optical surface supported by a reinforced shape memory resin composite substrate have the potential to meet the requirements for rapid fabrication of lightweight, monolithic, deployable, large optics. Evaluation has been completed for various composite constructions including shape memory resin, carbon fiber reinforcement and syntactic fillers bonded to the electroformed nickel surface. Results are presented from optical and structural performance tests on the materials to be used in 0.5 and 1.0 meter aperture deployable test reflectors.** *

I. Introduction

The Earth-Sun System Technology Office (ESTO) roadmaps identify measurement parameter needs for specific science themes, and a large number of the technology needs require larger apertures to meet the goals of higher spatial resolution, better signal to noise, and more frequent revisit times possible from higher orbits. These all require larger apertures, in many cases larger than can be packaged into existing launch vehicle fairings. Mass and production costs per unit area must also be reduced to maintain systems affordability. Replication processes can produce the required optical surfaces while reducing the cost and manufacturing time for large area optics. The goal of this study was to determine the applicability of a new class of shape memory materials that could provide a reflector substrate that could be stowed compactly yet deploy to a stiff and stable monolithic structure suitable for a wide spectrum of applications.

This study initially attempted to provide optical surface quality for deployable reflectors. Although surface replication to optical tolerances was achieved in the nickel over small surfaces, the developmental resins and fiber combinations used in composite replication processes were not able to support the nickel to the required surface accuracy. Work is continuing to improve cure stability and uniformity of the composite substrate to optical tolerances, however, the rugged metallization and surface accuracy achieved to date is certainly sufficient to meet the immediate need for deployable RF applications. Tests conducted on both flat and spherical material samples up to 0.3m indicate it is possible to achieve highly efficient, deployable, diffraction limited reflector surfaces on 1 meter diameter Ka band reflectors with areal densities in the range of 0.7kg/m^2. A 1m diameter demonstration model is currently being fabricated.

Large aperture, lightweight, deployable microwave antennas with high surface shape accuracies have been identified by ESSD as a critical enabling technology for the realization of a number of science measurement objectives at frequencies in excess of 200 GHz. Compact launch envelope stowage, reliable and precise aperture deployment, low areal density are also highly desirable features.

Shape memory composites provide notable advantages over other composite optics in deployed applications. A conventional composite requires significant stored energy for the stowing and deployment, and a complex mechanism for slowly releasing the stored energy in a controlled fashion. The optical surfaces must be protected during launch. A shape memory optical structure can be stowed, and structurally rigidized in a configuration that protects optical surfaces from abrasion or damage. A monolithic deployable reflector will not have the artifacts associated with segment edges.

A. Application to Earth Observing Missions.

Earth observing missions urgently need to reduce payload mass and mission cost, while at the same time increasing spectral and temporal resolution. Lightweight deployable composite mirrors are ideally suited to these requirements. Missions previously limited to LEO can now afford the mass and cost of larger apertures needed at higher orbits to take advantage of greater observing time, thermal stability, and lower gravity disturbances.

Soil moisture and precipitation monitors require apertures in the range of 4 meters or larger to obtain adequate spatial resolution. Improved measurement accuracy of sea ice extent, snow cover, snow water equivalent and ocean surface winds are possible by employing larger reflectors on both radiometers and scatterometers operating in the Ku-band (~13 GHz).

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II. Structural Concepts

Shape memory properties have been added to the cyanate ester based polymers used for conventional fiber reinforced composites used for space structures. This investigation combines a substrate of reinforced shape memory composite materials with a thin (~0.020mm) nickel layer. The lamination provides a high stiffness composite substrate for surface shape control and pointing agility, while the thin nickel optical surface provides a flexible, durable, and low stress optical surface.

Reflectors may be fabricated, heated, rolled, and "frozen" in a compact configuration to stow the optic for launch as in Fig. 1. The mirror is deployed by reheating in orbit, releasing the memory shape locked in the composite when it was initially cured on the replication mandrel.

Special requirements of the composite became evident during stow and deployment tests. During a deformation,

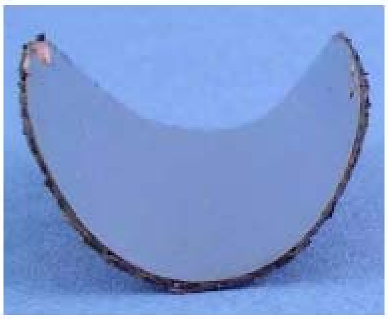

Fig. 1. A composite mirror of shape memory composite holds a stowed shape until deployment in orbit.

the softened resin must allow fibers to move within a limited area while accommodating tensile forces on exterior radius, and compression on the interior surfaces. The resin has a limited elastic deformation range, typically 10-40%, [1] and when combined with minimum bend radii for reinforcing fibers suggest that the fiber orientation and weave now has the usual requirements for isotropic performance when rigidized, but must also accommodate significant fiber movement during deployment.

Several conventional composite structures using varied formulations of shape memory materials were investigated to capitalize on the particular properties and limitations of the resins. Critical parameters required for deployable reflectors were measured for unidirectional fibers, filament winding, three dimensional weaves, using large and small tow sizes and various resin ratios were measured. In addition, several unconventional constructions were also tested. These included syntactics with silica and carbon microballoons, fiber reinforced syntactic laminated between carbon fiber reinforcements, and various resin reinforcing fillers, including chopped fibers and carbon nanofibers.

III. Replication technology

Space-based optical instruments have been increasing in size to gain corresponding increases in performance necessary to meet performance goals. Accurate deployment of large optical surfaces is required to fit larger apertures within a limited fairing volume. Composite replica mirrors are a relatively new class of super lightweight optical mirrors with areal density in the range of 1-5 kg/m^2. They are fabricated by replication from a polished mandrel, using multiple layers or plies of fiber-reinforced polymer composite materials. The layup of composite materials on a single polished mandrel provides the opportunity for manufacture of multiple optics from a single, optically figured master. Large apertures may be assembled from multiple, easy to manufacture mirror segments. Requirements for these reflectors include surface figure accuracy and stability, surface smoothness, minimal thermal expansion and distortion, stiffness, strength and durability, low areal density, and resistance to atomic oxygen and solar radiation [2]. High accuracy replicated optical surfaces on graphite reinforced composites has been demonstrated and is reported in [3].

Replication processes provide optical designers with alternate choices for telescope mirrors that are lighter, cheaper, and faster to produce than conventional metal and glass mirrors, and easily made in multiple identical units [4]. Composite Mirror Applications, Inc. (CMA) has recently demonstrated a 0.6-m diameter composite replica mirror with an areal density of 2 kg/m^2, which is 1/3 to 1/10 that of other "light-weight" mirror technologies. A 2-m composite replica mirror recently fabricated by Composite Optics, Inc. for the European Space Agency's Herschel Space Observatory (formerly called FIRST) demonstrated that duplicate composite mirror facesheet segments could be replicated off a single small mold. An areal mass of 10 kg/m^2 was achieved which met all optical performance requirements for the infrared telescope system. Deployable composite replica optics have also been manufactured by making them thin and flexible enough to roll up, with deployment consisting of releasing them to spring back to their original shape [5].

IV. Research approach

Existing high-quality optical replica electroplating capability at Northwestern University and proprietary SMP materials developed by CRG were combined. Although there is an existing basis for the technology, the development of shape changing composite structures is in its infancy. There is a lack of structural models for describing composites during soft resin states and while deformed and locked in a stowed configuration. Our goals here were not to duplicate the replication accuracy achieved by others, but to identify materials and constructions that are compatible both with reliable replication processes and shape memory materials so they may be incorporated in a large deployable surface.

We began with identification of prospective applications, including both optical (light bucket) collectors and microwave reflectors. Typical requirements for rigid collectors were assembled to serve as target goals. These requirements included surface accuracy, reflectivity/conductivity, surface scatter, mass, and resonant frequency. Then, the deployment requirements including stow volume, repeatability, creep, thermal and structural fatigue resistance, and space durability were considered and target goals identified. These collected requirements were prioritized, focusing on the specific aspects required to make functional shape memory structures. Modeling was used to confirm performance when scaled to larger apertures and further defined the critical material parameters necessary to meet requirements for a full scale unit. We developed specific key processes, such as reliable adhesion of a metal to flexible composite, and concepts for demonstrating heating, and tooling for stow and deployment. The designs and processes were tested in small samples, then on larger pieces of about 30 cm, and are now being incorporated in a 1 m deployable reflector.

A. Structural Modeling

Models were developed in parallel with the testing effort. The main goal was to use the material, thermal and structural performance models to predict deployment deformations given a certain design. Characterization and definition of properties, both material and thermal, of process procedure and control, and of geometry of the mirror was the expected outcome of the modeling effort.

The first model was a simple Excel based model that incorporated thermal, material and structural properties. Formulas were taken from Roark [6], Sarafin [7] and Timoshenko and Goodier [8]. Material and thermal properties were determined by experiment. Geometric properties included spherically shaped mirrors with each layer assumed to be homogenous but modeled separately from its neighbor.

This model was run for an early sample made of Styrene SMP with 3D Weave Carbon. Simulation of the deflections ("roll-up") of convex samples in the oven resulted in modeled data within 50% of the experimental data. Both temperature (110°C as used in the experiment) and additional force due to the roll up were incorporated. The change in "length", or in this case, diameter, of flat samples due to temperature change was within 20% of experimental data.

A more rigorous model using finite element and thermal models was developed to help define hardware parameters and provide information for future sample preparation. The model was prepared and run for both typical resins and fibers in symmetrical constructions, and for the lay-up and constructions being tested. Resin rich construction was chosen for its match to the CTE of the nickel layer. Two layers of triaxial open weave (1k tows of T300 fiber at 0+/-60 degrees) with measured modulus of 138ksi, and a density of 2.3g/cc provides a deployable reflector surface with an areal density under $0.7 g/m^2$. The first mode resonance shape is shown in Fig. 2.

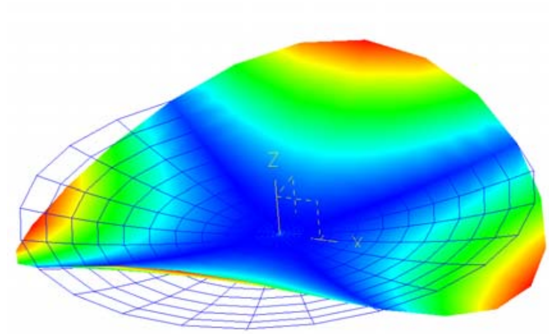

Fig. 2 Typical first mode frequency for very lightweight, 2 layer triaxial weave center mounted 1m reflector with shape memory resin is 0.26Hz.

B. Thermal Modeling.

Thermal deformations were modeled to demonstrate that isotropic constructions would maintain surface distortions within the required parameters. The test cases showed several isotropic layups would maintain surface accuracy in the range of +/-20µm. The quasi-isotropic constructions investigated with a 20µm nickel surface predict a 5m reflector will deflect less than 13µm maximum under a 10°C temperature gradient.

Thermal modeling identified heater requirements for deployment in space in a nominal low earth orbit thermal environment. The current resin formulation requires temperatures of about 200°C for deployment, and for typical low earth orbit, this requires about 1000W per square meter of reflector area. Deployment may occur in stages as power is available, but this power level is impractical for small spacecraft. The absorptivity-to-emissivity ratio properties of the composite were modeled to allow deployment using only sunlight ($1368 W/m^2$) rather than using embedded heaters. This solar heating approach is scalable to accommodate any large size reflector. Commercially available foil tape applied to the composite will produce 200°C resin temperatures, with the covered fraction of the surface adjusted for the desired temperature, rate of heating, and the actual orbit parameters. An MLI sunshield would be deployed to protect the reflector from further heating.

V. Investigation of Shape Memory materials

Recently developed shape memory polymer (SMP) materials maintain the high modulus of more conventional materials when below the glass transition point (T_g), yet demonstrate low modulus and the memory capabilities when heated. Shape memory materials are similar to traditional fiber-reinforced composites except for the use of shape memory polymer resins. The structure may be packaged compactly for launch and subsequently deployed to the as-cured shape by releasing the stored strain energy through application of heat.

A. Shape Memory Characteristics

The unique properties of the shape memory resin enables SMP materials to achieve high packaging strains without damage. Strains are induced by elevating the temperature of the SMP material and then applying a mechanical force. The shape memory characteristics enable the high packaging strains to be "frozen" into the SMP by cooling. Deployment (i.e., shape recovery) is effected by elevating the temperature. At normal operating temperatures, the performance of SMP materials follows classical composite laminate theory. At higher temperatures, SMPs exhibit dramatically reduced stiffnesses due to significant matrix softening of the resin as shown in Fig. 3. The localized heat application allows for unique stress/strain relief versus normal composites. Addressing the mechanics of the "soft-resin" will enable the SMP materials to provide repeatable stowage and deployment performance without damage and/or performance changes.

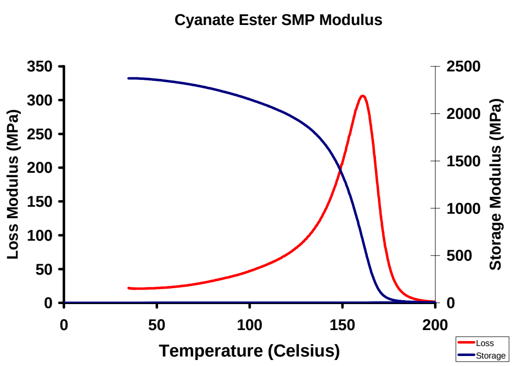

Fig. 3: Modulus Curves for Baseline Cyanate Ester SMP, T_g = 160°C

Mirrors were formed by substituting SMP materials for the usual resin matrix in the composite. The polymer resin selected for these mirror fabrication tests is a cyanate ester, modified for shape memory properties by Cornerstone Research Group, Inc. (CRG). Other than shape memory characteristics, resin properties mimic conventional cyanate esters. As previously reported the original formulation demonstrated strain recovery of approximately 10%. Modifications have been made to improve the ultimate strain without damage to over 30%, see Fig. 4. The majority of the effort has been done using woven fabric composites, as we have used, Fig. 5. The diverse selection of fabrics available provides quick tailoring of

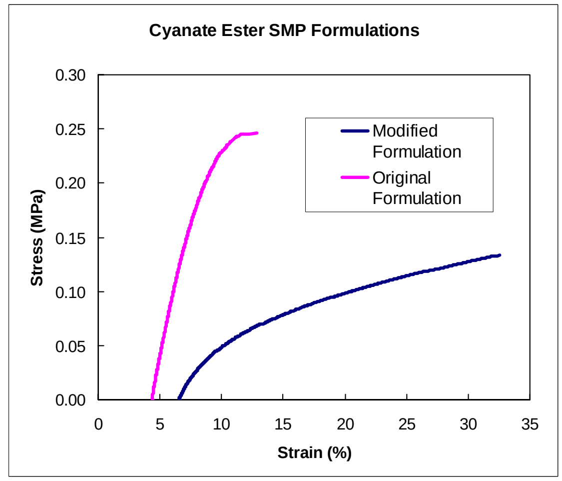

Fig. 4. Improved resins have strain capability over 30%

Fig. 5. Resin rich triaxial weave combines sufficient stiffness and with shape memory properties.

composite properties such as stiffness and coefficient of thermal expansion (CTE). Some fabrics tolerate stow and deploy cycles better than others, depending on weave geometry.

B. Reflective Surface Replication

Two composite metallization schemes have been developed. An electroformed metal surface may be created on an optical mandrel, and the composite applied to the back surface, or metal is applied to a replicated composite surface. The metallization processes demonstrated on 30 cm reflectors are being scaled up to allow fabrication of 1m demonstration models. This system at Northwestern University is based on sulfamate nickel electrochemistry that results in the lowest residual stresses in the plated metal. Bath temperature, pH, and plating current are monitored and controlled for a zero stress electroform. Fiber print-through of fiber-rich composites is much reduced by having a thicker electroformed metal reflecting surface layer, but limited by stow flexibility and residual deformation due to microyield of the thicker nickel [9].

C. Plasma Etching for Nickel-Composite Adhesion

The etching tooling has been scaled up to etch patterns (using stainless steel mesh as a mask) on 30cm convex surfaces (mirrors) and scale up to 45cm. mirrors in the sputtering chamber.

The mirror is mounted on a rotating axis facing of one of the magnetron cathodes, maintaining its geometrical relationship to the cathode while etching.

The plasma is created with a application of RF power to the substrate. The etch depth for a surface is dependent on the power density over that surface and the etching time. We achieved an etch depth of about 0.04 to 0.6 microns through the mesh.

VI. Test Item Fabrication

Requirements for a composite reflector were specified using existing materials with known properties and using a demonstrated mirror electroforming process. Control of interface stresses between the nickel and composite has been the major focus of the initial tests because of the criticality to success, and the novelty of the approach. We have defined the process requirements for the nickel, considering mandrel separation, adhesion, roughness, thickness, and stress control, according to the current best practice optical plating processes. Composite goals include definition of requirements of the composite substrates that currently limit application of composite optics. This includes dimensional stability during cure, low thermal expansion coefficient, high specific stiffness, minimal fiber reinforcement print-through, low or no micro-cracking, low outgassing and low moisture uptake, compatible processibility and processing time, evaluation of alternate reinforcement materials and reinforcement architectures, fibers and fiber combinations, nano-reinforcements.

A. Nickel Surface Replication.

The 12-inch-diameter concave mirror was replicated by electroforming nickel using a commercially available convex stainless steel mirror as a master, and processes developed at Northwestern for manufacture of low stress X-ray optics.

B. Adhesion of composite to electroformed nickel.

Surface treatments including abrasion, sandblasting, acid etch and ion etching of the electroformed nickel surface to improve the adhesion were investigated. Mechanical abrasion of the surface by sand blasting, or the use of fine sand paper or diamond paste somewhat improved the adhesion, but was not reproducible and in some instances damaged the optical surface. Acid etch improved the adhesion of the composite to nickel, but it was not as significant as plasma-etch.

Plasma etching was applied to the rear of the nickel electroforms, resulting in the patterned roughness seen in Fig 6. The stainless steel mesh produced the regular grid pattern seen in the profile (Fig. 7), while the ion etching produced a cratered appearance between the areas masked by the mesh. Both patterns contribute to the excellent adhesion we observed.

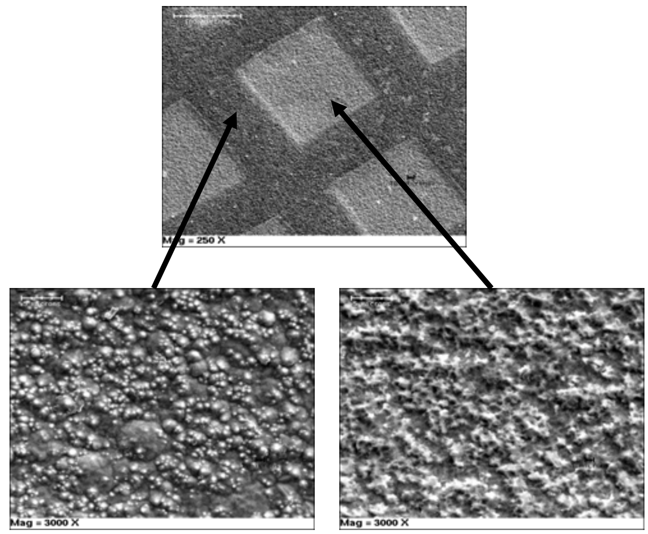

Fig. 6. SEM micrographs of the plasma-etched surface of electroformed nickel. A – 250X magnification, surface etched through the mesh (dark - as plated, light – etched surface); B – as-plated nickel (3000X magnification); C – etched surface (3000X magnification)

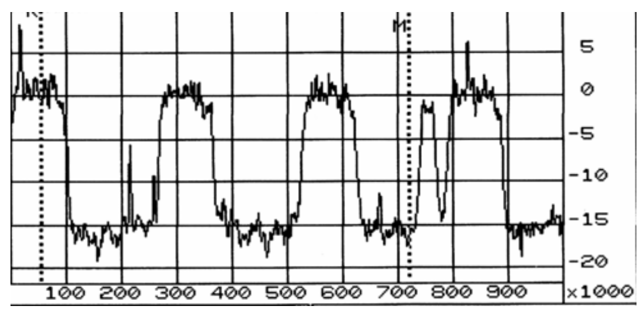

Fig. 7. Profilometry of the surface of plasma-etched electroformed nickel (Horizontal axis –distance in microns, Vertical axis – profile in angstroms)

C. Stow and deployment process

Stow tooling and mandrels are necessary for supporting the composite, to prevent sharp bends and buckling. Bending forces need to be applied uniformly across surfaces since the softened resin provides little constraint on fiber motion.

Temperature control is required during all phases of the stow and deploy process to prevent cracking of the resin due to cooling too fast or applying excessive forces when cooled.

D. Summary of Results

Shape memory properties of the composites have been demonstrated on 30 cm reflectors replicated from spherical mandrels. Surface repeatability appears adequate to meet requirements of a Ka band reflector when scaled to a 1 m diameter. This will be verified when the 1 m demonstration model testing is completed in June, 2005.

Critical to validating the concept was the need to verify adhesion of disparate materials as composite and nickel. Surface accuracy, smoothness, and material outgassing goals were largely accomplished. Investigation is continuing on nanofiber and fabric reinforced materials, and symmetric layers to isolate the optical surface from the reinforcing layers.

1) *Shape Memory properties*: Repeated stow-deploy temperature cycle tests showed flat sheets of the composite were not damaged by repeated rolling up the laminated mirrors to 50mm radius. Spherical pieces currently show about 10 times this value demonstrated in Figs. 8 and 9. A 100mm graphite fiber reinforced sample exhibited deployed positional repeatability of 0.1mm after more than 10 bend and deploy cycles of 180 degrees. Further measurements are planned to confirm the repeatability for various reinforcing structures and formulations, and measurement of creep and environmental stability in vacuum.

2) *Lamination Integrity*: Adhesion of composite to nickel has been accomplished through roughening of the nickel before composite lamination, with ion etching through a mask providing the best results. Repeated temperature and bending cycles (-18C to +110C and 100mm radius bends) demonstrated tenacious adhesion Compliance of the soft resin reduces interface shear loads within adhesion limits during deformation in the soft state, and additional thermal or mechanical loads does not cause delamination. Resin structural failure occurs before ion etched nickel delaminates. Composite structures have been fabricated with CTE values spanning a range greater and lesser than nickel. Fine tuning of the resin ratio, consistent with deployability limits, will match the composite and nickel CTE to reduce the internal thermal stresses and figure changes.

3) Replicated low scatter surfaces: Mandrel roughness was reproduced with a 2nm RMS replica

Fig. 8. 32 cm f/2 mirror substrate deployment Stowed (left) and deployed by heating (right)

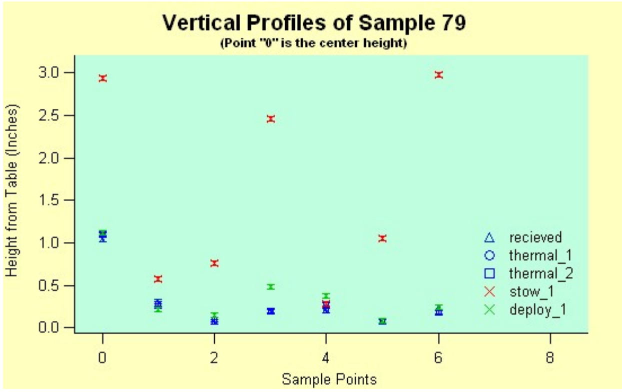

Fig. 9. An early test mirror demonstrated return to the as-cured shape within 1mm. Current constructions provide improved repeatability.

surface roughness. The laminated nickel optical surface does not permanently deform or wrinkle during roll-up of the optic as long as there is no delamination. Print through is still noticeable, but was reduced through the common practice using layers of high resin content composite adjacent to the nickel surface. The surface scatter and print through is adequate for microwave and many light bucket applications, but further development should include low-print-through processes with shape memory resins. Increased nickel thickness requires balancing the need for improved surface smoothness and reduced deployability.

4) Materials

A range of resins, fibers, fillers, and syntactics were tested to determine effects on structural and shape memory properties. Thin layers of triaxial (0 +60-60 deg) weaves show adequate stiffness and deployment repeatability. Filament wound and syntactic core constructions have also been fabricated, but require more development. Resin formulations with greater toughness and elongation are being developed, and additional work in nanofiber reinforced resins will further increase the range of resin capabilities.

Material outgassing has been verified to meet acceptable range in NASA specified tests for Total Mass Loss (in the range of 0.29 – 0. 059%TML) and measured Condensed Outgas Products below 0.03%. We anticipate this material will demonstrate adequate durability in the space environment consistent with its similarity to current cyanate ester formulations upon which SMP is based.

VII. Future Directions

Scaling the results of these small samples to predict behavior of 5m and larger structures will be necessary to fully utilize the deployable properties. Improved optical figure control allows wider use of the technology in shorter wavelength bands, but requires much more precise process controls and modeling prediction capability. Current deployment repeatability data suggest microwave reflectors spanning over a meter will maintain sufficient accuracy for aperture limited resolution typical of current composite reflectors even after stow and deployment.

Structural properties and dynamic response while the material is in a stow configuration needs to be better understood. Mechanical design to incorporate stiffening elements, active actuators to overcome residual resin hysteresis will expand the range of future applications at shorter wavelengths.

Future work includes the use of a formal Integrated End-to-End Modeling (IM) environment being developed at Ball to handle complex thermal-structural interactions to predict surface deflection and reflector image quality. The Ball IM is a Simulink / MATLAB based environment that provides an end-to-end system engineering tool. This integration capability for coupled models permits the user to perform both time simulations and analytical work in the spatial and temporal frequency domains. The individual models from structural dynamics, optics, controls, signal processing, detector physics and disturbance modeling are seamlessly integrated into one cohesive model to efficiently support system-level trades and analysis for extremely flexible membrane optics such as being developed here. The IM can include theoretical models for items such as the effect of material microyield [5] on the mirror wavefront error. With that information, we can trade the material properties needed for the desired stowed geometry, vs. system resonant frequency, or thermal stability.

VIII. Conclusion

Shape memory materials are becoming available and better understood for space structures have applicability to large deployable optics. New mission concepts involving novel stow and deployment schemes may be possible given increased design latitude. Shape memory materials incorporated replication processes have the potential for further exploitation to expand the range of applications for composite optics.

A one meter metallized reflector is being fabricated using the processes developed and will be tested in the next few months to compare its performance of a rigid Ka band reflector both before and after stow and deployment.

Acknowledgment

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References

[1] Varlese, S.J., Ulmer, M. P., Hardaway, L. R., Everhart, M., Vaynman,S., Emerson, G., Graham, M., Echt, J., Farber, M., Vining, S., Laminated electroformed shape memory composite for deployable light-weight optics; SPIE Proceedings, 5542-50, Aug 2004

[2] Composite Mirror Applications, Inc. Web Site, http://home.earthlink.net/~bromeo/, 2000.

[3] Semi Rigid and Adjustable CFRP Membrane for Radio Telescope Applications, D. Giles and S. Kulick, Composite Optics, Inc., Final Report, NSF SBIR Phase II Contract DMI-9801169

[4] Ulmer, Melville P., Altkorn, Robert I., Kibblewhite, Edward D., Varlese, Steve, Replication as an alternative approach for large segmented telescopes, Large Ground-based Telescopes. Edited by Oschmann, Jacobus M.; Stepp, Larry M. Proceedings of the SPIE, Volume 4837, pp. 786-794 (2003).

[5] R. C. Romeo, A. B. Meinel, M. P. Meinel, and P. C. Chen, Ultralightweight and hyperthin rollable primary mirror for space telescopes," in Proc. SPIE Vol. 4013, p. 634-639, UV, Optical, and IR Space Telescopes and Instruments, James B. Breckinridge; Peter Jakobsen; Eds., 4013, pp. 634{639, July 2000.)

[6] Young, W.C., Roark's Formulas for Stress and Strain, 6th edition, McGraw-Hill Book Co., NY, 1989.

[7] Sarafin, T.P., editor, Spacecraft Structures and Mechanisms, Microcosm Press, CA, 1995.

[8] Timoshenko, S.P. and Goodier, J. N., Theory of Elasticity, 3rd edition, McGraw-Hill Book Co., NY, 1934.

[9] Domber, J. L., Peterson, L.D., Implications of Material Microyield for Gossamer Optical Reflectors, AIAA 2002-1503, 43rd Structures, Structural Dynamics and Materials Conference, 22-25 April 2002, Denver, Colorado